A literature review on low-cost sensors with the Internet of Things application in indoor air quality monitoring in residential buildings

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Introduction

Good indoor air quality (IAQ) is the basic requirement for guaranteeing well-being and a healthy lifestyle. In residential buildings that are private, autonomous and occupied spaces for most of the time, keeping a good IAQ level is necessary, especially when there are children, elderly or other vulnerable users. Within the development of gas sensors, its low-cost feature and Internet of Things (IoT) application make it affordable, flexible and feasible even for ordinary occupants to do IAQ monitoring in their homes.

In this work, a systematic literature review focus on the monitoring performance of IoT system with low-cost sensors (LCS) in the research of IAQ monitoring in the residential buildings. It aims to find answer to the following questions:

- How is the performance of IoT system with the low-cost sensors in the IAQ monitoring in residential building?
- What type of low-cost sensors are used in the research?
- What pollutants are those sensors measuring or what are the current sensors are able to measure?
- Are they affordable or suitable for IAQ monitoring in the residential buildings?
- What are the current limitations for IoT system with LCS?

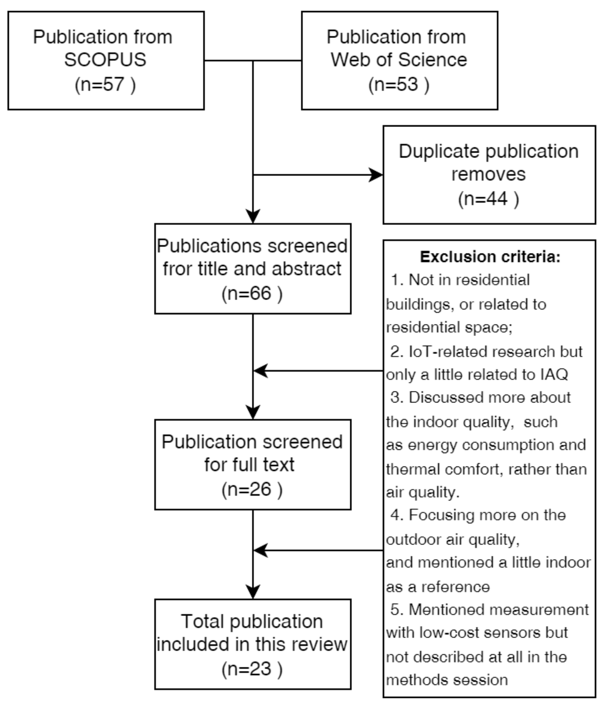


Fig 1. Flowchart of the bibliographic review process.

Method

This systematic review searched papers from 2 databases, SCOPUS and Web of Science. The queried used the 3 groups of keywords for both 2 databases:1. "IAQ" OR "indoor air quality"; 2. "internet of things" OR "IoT" OR "low-cost sensor*"; 3. "resident*" OR "home*" OR "house*" OR "domestic". These quried in the database only used "open access" as filter used during the search, and there is no other filter on time, language or field. The quries were searched around May 2023.

In the quries result (Fig. 1), there are 57 publications from SCOPUS and 53 from Web of Science. After removing the duplicated publications (n=44), there are 66 publications for in the 2 rounds of screenings. The exclusion eliminated during the screening that: 1. not applied in residential buildings; 2. related to IoT, but mentioned little about IAQ; 3. more related to thermal comfort and energy consumption rather than IAQ; 4. more about outdoor air quality but not indoor; and 5. used LCS but not described at all in the main texts. Only those papers with targeted contents are included. After the 2 rounds of screening on their titles, abstracts and full texts, a total number of 23 papers are included in this review.

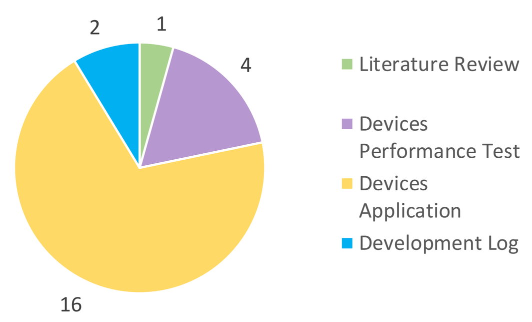


Fig 2. Theme of the included publications

The included papers

Based on the themes of the included paper, they can be classified into 4 different types of research (Fig. 2):

1. Devices application (n=16): in these researches, they applied existing or developed devices (or systems) based on low-cost sensors as a tool to the environmental monitoring work
2. Devices Performance Test (n=4): in these researches, the aim is to test the performance of devices or IOT systems which are developed by the research groups.
3. Development Log (n=2): in these research, the main contents are recording whole processes and details about the devices or system development, including their sensor selections, the architecture of the IoT system, outcomes and performance, etc.
4. Literature review (n=1): in this research, the aim is to summarize the applications of different sensors and the performance of existing commercial devices.

The included literature review in published in 2022, and its aim is to evaluate and compare the performance of LCS against other instruments in the application research, but this review focuses on LCS application in the residential buildings and its potential to be extensively applied for long-term IAQ domestic monitoring. Since there are some duplications of included publications, the following result didn't count in the results found in this review, only text information extracted in the discussion.

The publications are from 2017 to 2023, with the nunber for publication (Fig. 3) keeping increasing till the time of review quries in May 2023.

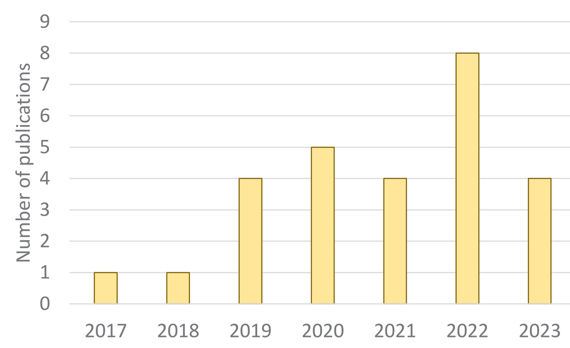
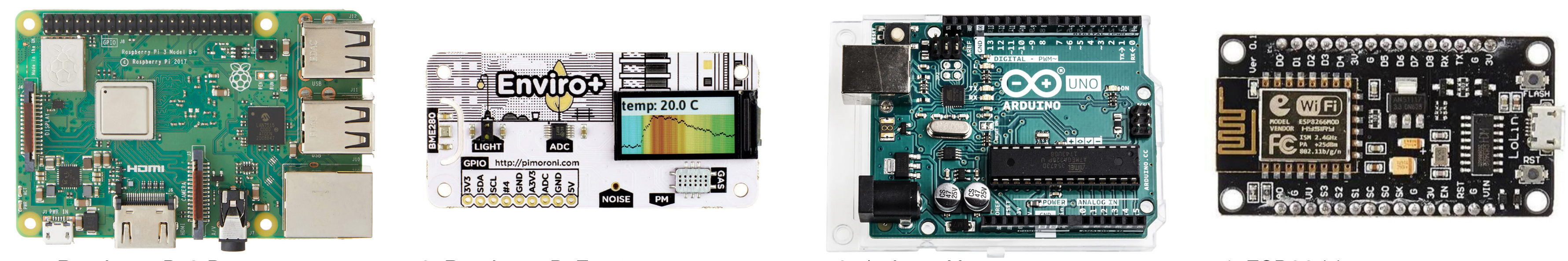


Fig 3. Year of the included publications

Micro-Control Unit in device development



1. Raspberry Pi 3 B+ 2. Raspberry Pi Envrio+ 3. Arduino Uno 4. ESP8266

Fig. 5 Microcontroller mentioned the included publications

Apart from the air sensors, another core component in the IoT system with LCS is the Micro-Control Unit (MCU, or Microcontroller). In the research on device performance test and development log, they also introduced the MCUs they used in the development, which are Raspberry Pi 3 B+; Raspberry Pi Envrio+; Arduino Uno; and ESP8266, as shown in Fig. 5. Those MCUs are also low-cost, user-friendly and popular in the community of DIY developers, and there are already many existing resources, tutorials ready online. Non-commercial applications are capable of IoT developments.

On the other hand, the research with commercial devices didn't mention the MCU types, but for commercial devices, they usually adapt the core chips by themselves in order to minimize the size of the device and the cost of materials. For example, ESP-12E is the core of ESP 8266, and the Printed Circuit Board (PCB) can be designed and integrated with all needed sensors of the devices. Also, there are many chips, such as Netbook, Wasmote, TI MSP430, etc. with different data transmission protocols, Bluetooth, Zigbee, etc. They have features with less energy consumption and longer distances of data transmissions.

Unclear definition of "low-cost"

Table 2. Cost of several commercial devices

Name of sensor or devices	Parameters T	RH	PM	VOC	CO2	Retail Price
Commercial Devices with Low-Cost Sensor						
Netatmo (inside unit)	■	■			■	$165
Awair 2nd Edition (Awair)	■	■	■	■	■	$199
Foobot	■	■	■	■	■	$199
Kaiterra Laser Egg (Kaiterra)	■	■	■		■	$199
AirU			■			$200
AirVisual Pro (AirVisual)	■	■	■		■	$269
uHoo (uHoo)	■	■		■	■	$329
UMDS			■			$366
Clarity Node (Clarity)	■	■	■		■	$1,000
Research Level Devices for Reference						
AirMetrics MiniVol			■			$3,650
TSI DustTrak II			■			$5,000
GRIMM 1.109			■			$12,000

Even if all the research mentioned the "low-cost" air sensors, their different definitions of the "low-cost" concept are quite different. For example PM sensors, Alphasense OPC-N3 cost around GBP250, but Shinyei PPD42NS (≈20€) dust sensors, Sharp GP2Y1010 (≈10€), Honeywell HPM series (≈60€), PMS sensors (≈10€) can be much cheaper, even if the accuracy is not as high as OPC-N3.

Also, for the commercial devices, their price (Table 2) are not very economical for single users. 160 to 300$ for 1 single device, and for an entire house there may be at least 3 devices, in the living room, bedroom and kitchen. They are still expensive even if they provide high-quality services.

Besides, the cost of the sensor and the price of devices highly depend on the region and local market. For example, similar household IAQ devices from China (28~38€) can cost half more or even triple in Europe (40~120€), which may also be due to the local tax on electronic devices.

In general, the unclear definition of "low-cost" can make it not so affordable for ordinary residents. The sensors with lower accuracy but economical price are probably not capable for research purposes but can be enough for long-term monitoring in residential buildings.

The increase from device cost to commercial price

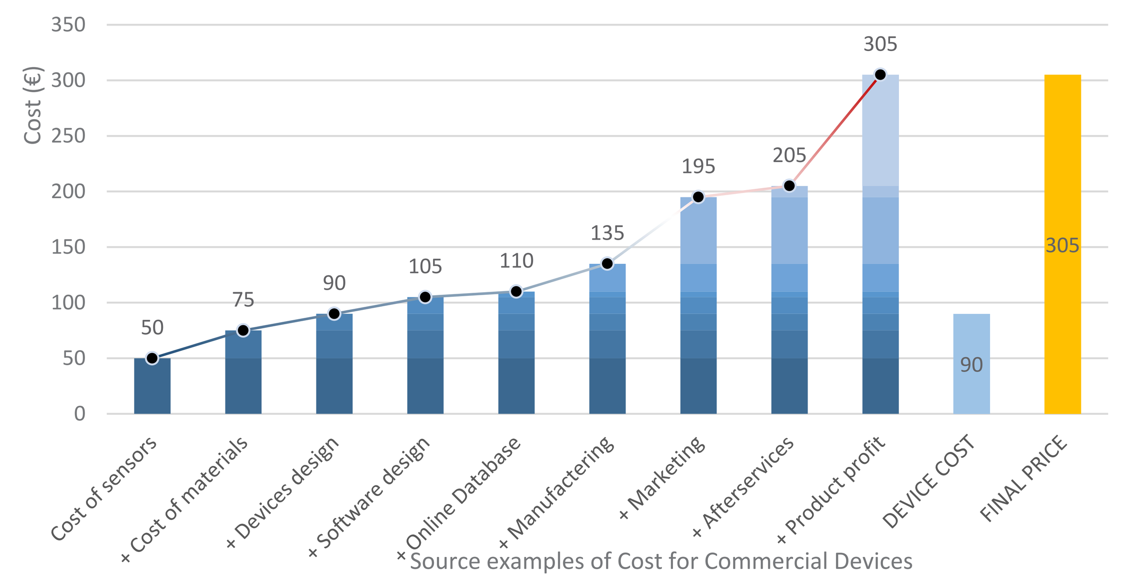


Fig 6. Final price of 1 single IAQ commercial devices accumulated from all kinds of costs (Values are reference numbers, real values depends on regions, devices and qualities)

Consumer-level IAQ monitoring systems or products are still not so easy to provide to the market of the private users like residential space. One single devices with basic monitoring parameters with hundreds of Euros price will keep most individual consomers away.

Even if the sensors and other related hardwares are low-cost and affordable for consumers, the formal products are other things. There are cost on devices design, manfactering, etc.; cost on software design, server maintainence, etc.; cost on marketing and afterservices, etc. Then the profits added to the product. So the price increases dramatically when the monitoring device turn from a box to a product, from 30 Euro to 300 Euro, which is the cost to the customers in the end.

The condition in the office building or the school might be different, after all, such a monitoring system in a building with public function can be splited or afforded by the oranizations. But for the owners of private houses, How many residents would like to pay for the devices?

Monitored parameters and corresponding sensors

Among the included publications, their interested parameters (Fig. 3) can be classified into 3 types, (1) environmental parameters, (2) Air pollutants and (3) other parameters, with their corresponding sensors summarized in Table 1. Some sensors that have been mentioned multiple times in different publications are recorded only once in this table.

Particulate Matter (PM) and CO2 are the main focus of those research, far more than the following VOC, CO and NO2. This is not only due to the numerous indoor sources of PM and CO2, but also the better functions, more options and lower costs of LCS for PM and CO2, which allow the extensive research applications.

Most sensors in Table 1 have a manufacturing company or a brand, such as Bosch, Sensirion or Plantower, who focus on the design and manufacture of sensors. Meanwhile, there are also some sensors adapted and manufactured based on the original sensor chips, with adapted modules, circuits or even whole devices, such as Purple Air and Adafruit, who work more on the sensor applications.

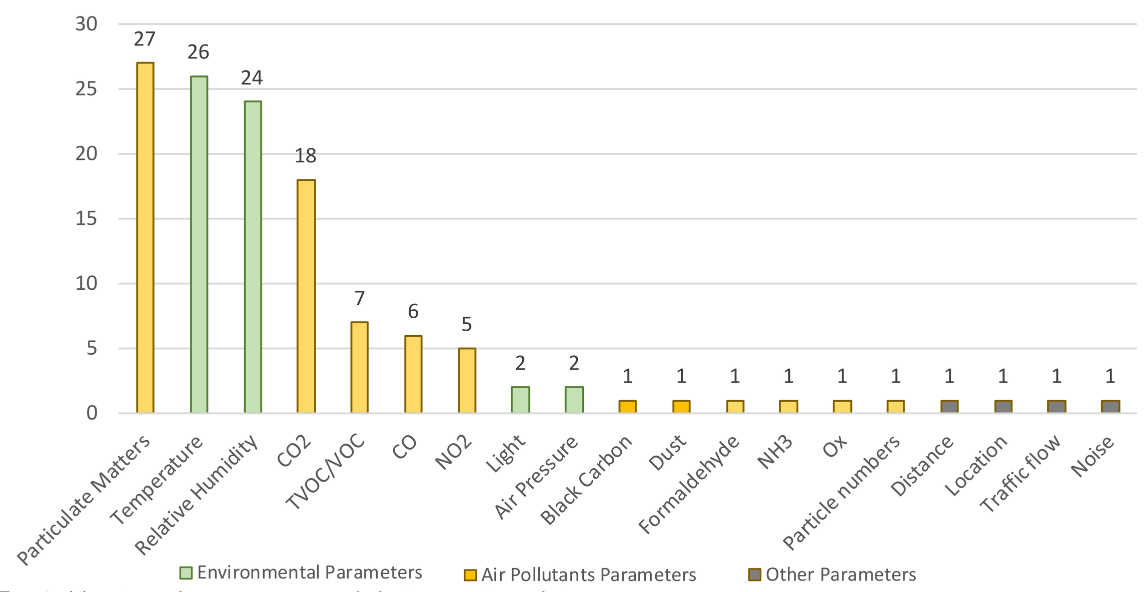
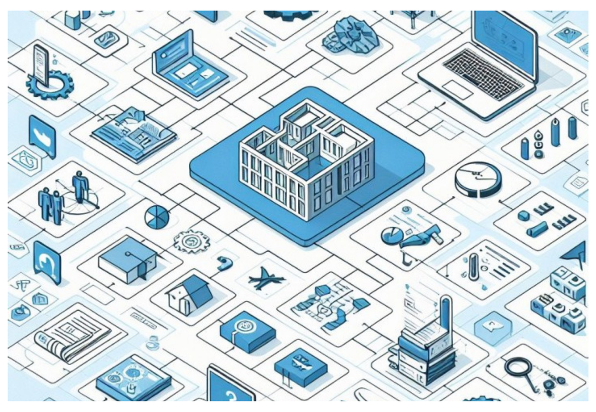
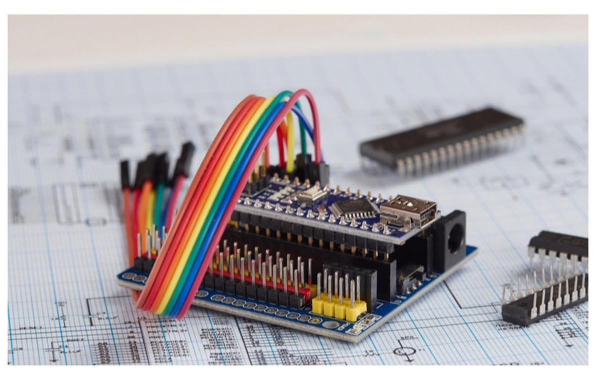


Fig 4. Monitored parameters and their mentioned times

Solutions for IAQ application in residential building





1. The integration into the existing building system or Building Information Modelling (BIM), such as the alarm or internet, can be much more economical than building individual system by users themself.
2. Local data storage and real-time display of IAQ results are more useful than the IoT remote monitoring feature in private residential spaces. And it can cut down the cost from the online database, maintenance and after-sales service, etc.
3. The modular design of devices and air sensors increases the flexibility and is more user- or developer-friendly. The standardized serial communication protocols for different sensors are equally important.

Table 1. Summary of low-cost sensors mentioned in the included research with their codes, brands and measurement parameters

Sensor or devices Code	Manufacturer or Brand *	Air Pollutant ** PM1.0	PM2.5	PM10	TSP	CO2	CH2O	TVOC	VOC	CO	NO2	NH3	Environmental Parameters ** T	RH	AP	Light	Other Parameters Distance	Altitude	Location	Traffic Flow
AHT10																				
AirCO2ntrol Mini	TFA					■							■			■				
AirVisualM25b		■	■																	
Amphenol Telaire T6703-5 K						■														
BH1750																				
BME-280	Bosch												■	■						
BME680													■	■	■					
BMP180	Bosch												■	■				■		
BMP280													■		■					
CO-B4	Alphasense									■			■	■						
CSS811								■												
DHT22	Aosong Electronics												■	■						
GP2Y1010AU0F	SHARP		■							■										
GPY1010AU	SHARP	■	■	■																
GPY1010AU0F	SHARP	■	■																	
HPM Series	Honeywell		■																	
HPM Series Particle Sensor	Honeywell		■			■							■	■						
HPMA115S0-XXX	Honeywell	■	■																	
iAM	ams								■											
K30	CO2meter					■														
Lit92	Littelfuse												■							
MH-Z14						■														
MH-Z14A						■														
MH-Z19A						■														
MICS-4514										■	■									
MICS6814										■	■	■								
MQ7																				
OPC-N3	Alphasense	■	■	■																
OPC-R1	Alphasense	■	■	■																
PASDD Model 11-D	Grimm Technologie	■	■	■	■															
PMS3003	Plantower	■	■	■																
PMS6003	Plantower																			
PMS7003	Plantower	■	■	■																
Purple Air PA-II	PurpleAir																			
S-300	ELT Sensor					■														
SCD30	Sensirion					■							■	■						
SCD40	Sensirion					■							■	■						
SDS018	NovaFitness	■	■	■																
SenseAir S8	SenseAir					■														
SGP30	Sensirion							■												
Shintei ppd42		■	■																	
SHT11	Sensirion												■	■						
SHT20	Sensirion												■	■						
SHT30	Sensirion												■	■						
SHT31-D	Sensirion													■						
SPS30	Sensirion	■	■	■																
SVM30	Sensirion							■												
T-110	ELT sensor					■														
WZ-S formaldehyde module	DART						■													
LTR-559 ***																■	■			
Ultimate GPS breakout ***	Adafriut																		■	
(VDS)-718,297 ***	CalTrans																			■

* The manufactors or brand are usually the company who manufacture and sell the sensors. The blank means in the papers the author didn't mentioned their manufactors.

** For air pollutants: PM for Particulate Matters; TSP for Total Suspandid Particles; CO2 for Cardon Dioxide; CH2O for Formaldyde; TVOC and VOC for (Total) Volatile Organic Compound; CO for Carbon Monoxide; NO2 for Nitrogen Dioxide; NH3 for Annomia; For environmental parameters: T for Temperature; RH for Relative Humidity; AP for Air Pressure;

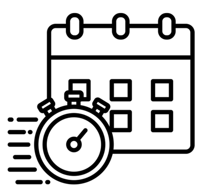
*** These sensors are not gas or air sensors but other devices mentioned for supporting air quality monitoring

Limitations to implement IAQ monitoring

1. Awareness of IAQ from users

And in general, IAQ is not always perceptible as thermal comfort. If the residents don't smell anything terrible, the IAQ will always be ignored until symptoms show up. However residential buildings are private spaces, managed by residents themselves and the reference values for pollutant levels aim to ensure the user exposure is lower than the level leading to symptoms. So awareness of IAQ from users is important in monitoring implementation.

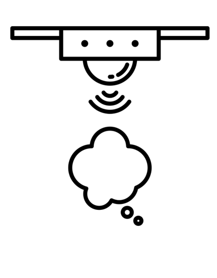
Besides, the monitoring of IAQ will cost extra money and time on purchasing and maintenance of the equipment, which mainly relies on residents' willingness.



2. The less urgency in needs for monitoring IAQ in residential buildings

Since the time people spends in the residential buildings are usually the rest hours, when they not always have fixed aim to achieve, and have more freedom in the house. For example, the users can control the ventilation whenever they want or move to spend time in another room to wait for ventilation.

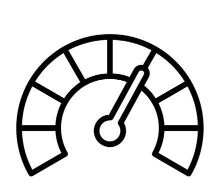
Some occasional peaks of pollutants and the exposures are not measurable in health condition.



3. Limitations on low-cost sensors types

As Fig.3 shows, PM and CO2 are the 2 most discussed pollutants. But it's not only due to the indoor source but also the limitation of pollutant types. It is the fact that there are the cost of PM and CO2 sensors are cheaper than all the other air sensors, and there are more options.

Also, the VOC sensors can detect only a few types of VOC pollutants and they cannot specify what is the level for which type. That is too general for describing the VOC level, and in some spaces, the pollutants are not able to be detected by the sensor even when the smells are strong.



4. Limitations on low-cost sensors range, precision and accuracy

Apart from the limitation on sensor types, the detection range of sensors and their precision is another problem. For example, many research reported that the PM sensor can only detect particles from 0.35 to 40 μm, so particles smaller than 0.35 μm are missed in the measurement.

Meanwhile, most low-cost sensors require calibration to ensure their precision. Some of them also need a certain period of pre-heating time before measurement to ensure accuracy. That means the user or developer still needs a professional device to calibrate them, before starting the measurement.